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Wrist Camera Orientation for Effective Telerobotic Orbital Replaceable Unit (ORU) Changeout

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Abstract

The Hydraulic Manipulator Testbed (HMTB) is the kinematic replica of the Flight Telerobotic Servicer (FTS). One use of the HMTB is to evaluate advanced control techniques for accomplishing robotic maintenance tasks on board the Space Station. Most maintenance tasks involve the direct manipulation of the robot by a human operator when high-quality visual feedback is important for precise control. An experiment was conducted in the Systems Integration Branch at the Langley Research Center to compare several configurations of the manipulator wrist camera for providing visual feedback during an Orbital Replaceable Unit changeout task. Several variables were considered such as wrist camera angle, camera focal length, target location, lighting. Each study participant performed the maintenance task by using eight combinations of the variables based on a Latin square design. The results of this experiment and conclusions based on data collected are presented.

Introduction

The initial reason that robotics was proposed for Space Station was to provide support to the assembly, servicing, and maintenance operations of the Space Station and its payloads. When NASA discovered, in 1989, that the amount of extravehicular activity (EVA) time needed on Space Station was four times more than originally estimated, the agency created the External Maintenance Task Team (EMTT) to investigate the difference between the estimates. Six months after its formation, the team produced a report (ref. 1) that quantified the amount of time needed to complete maintenance tasks both for EVA astronauts and the Space Station robots. The team concluded that the amount of crew time needed to perform Orbital Replaceable Unit (ORU) replacements by using robotics was less than or equal to that required for an EVA astronaut to perform these same tasks.

From 1988 to 1991, there were two dexterous robotic systems for Space Station construction/ maintenance: the Flight Telerobotic Servicer (FTS) from the United States (fig. 1) and the Special Purpose Dexterous Manipulator (SPDM) from Canada (fig. 2). After FTS was canceled by the U.S. Congress in late 1991, SPDM was the only maintenance robot for Space Station. As a result, all Space Station Robotic Interfaces were designed for the SPDM wrist camera.

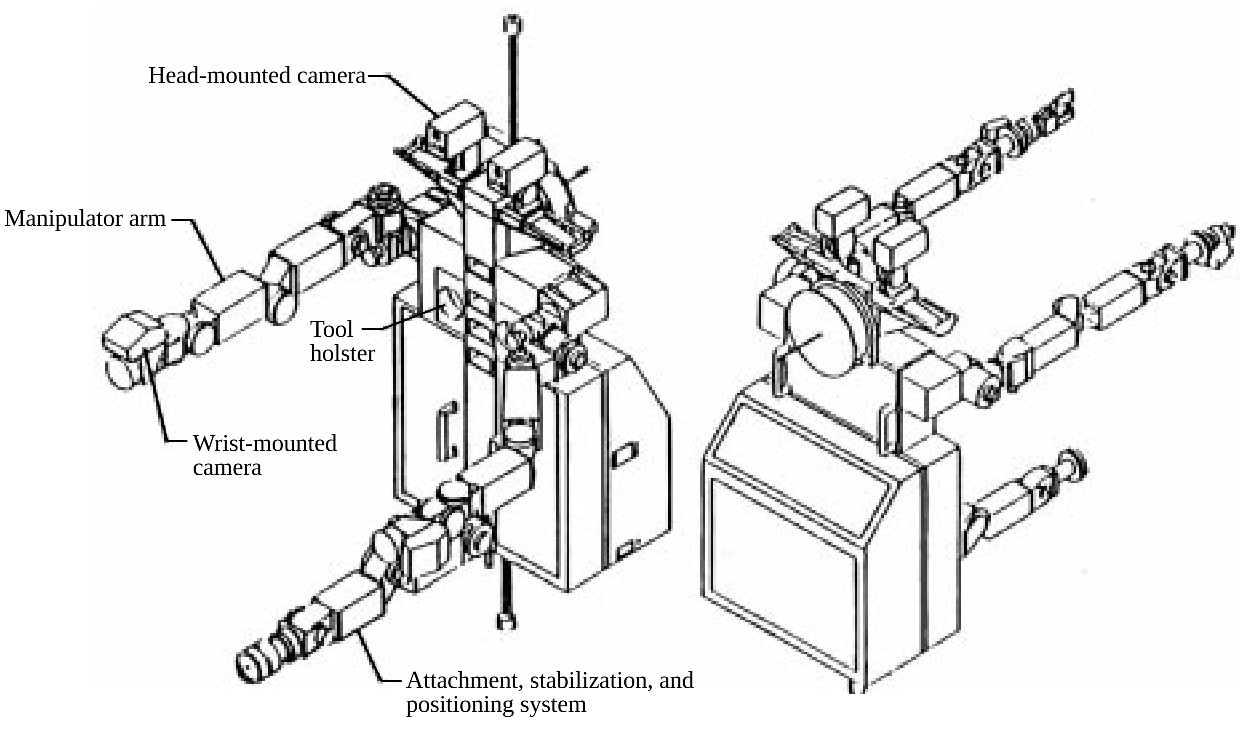

Figure 1. Flight Telerobotic Servicer. (From ref. 6.)

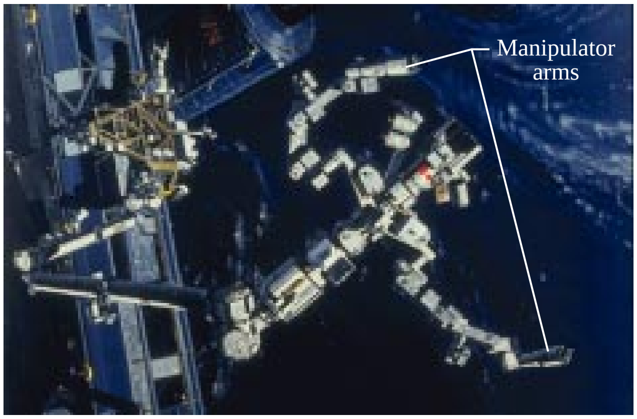

Figure 2. Special Purpose Dexterous Manipulator.

Canada has not guaranteed that the SPDM will be available for Space Station and is not scheduled to make a final decision until July 1997. To provide an alternative, the United States has proposed a lower cost version of the FTS, the American Fine Arm (AFA). To reduce costs, no major redesign of the AFA end-effector is allowed. However, since SPDM is still considered the primary Space Station robot, AFA must conform to all existing target designs.

Hydraulic Manipulator Testbed Project Description

The Hydraulic Manipulator Testbed **(**HMTB**)** (fig. 3) is a functional laboratory version of one arm of the Flight Telerobotic Servicer (FTS) flight system (ref. 2). HMTB shares the same kinematics as the flight system but uses hydraulic, not electrical, power for operation in a 1*g* environment.

The original purpose of HMTB was to provide a ground-based training environment for astronauts prior to flying the FTS. When the U.S. Congress canceled the FTS program, they appropriated $10 million to capture technology from the project. As part of this technology capture, Langley Research Center (LaRC) and Johnson Space Center (JSC) formed a partnership wherein, upon completion of the FTS system, LaRC would receive the HMTB and JSC would receive the flight arm and residual hardware (ref. 3). The purpose of this partnership was not only to complete the FTS system but also to transfer robotics control technology to NASA operations (i.e., Space Shuttle, Space Station). HMTB was installed at LaRC and incorporated in a laboratory which included a mock-up of the Space Shuttle aft flight deck (AFD).

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Figure 3. Hydraulic Manipulator Testbed.

Orbital Replaceable Unit (ORU) Changeout Task

On Space Station, over 8000 external Orbital Replaceable Units (ORUs) have been identified, and the estimation is that there will be 75 Remote Power Controller Module (RPCM) ORUs (ref. 1). The Space Station has an expected life of 30 years, but the RPCM life limit is 20 years; therefore, all the RPCM ORUs will have to be replaced during the life of Space Station. In a ranking of ORUs by the number of failures, the RPCM is number 10 out of 150 types of ORUs. Given such a high rate of failure, the RPCM will have to be serviced often, and it is for this reason the RPCM ORU changeout task was chosen for this study.

A typical RPCM (fig. 4) is equipped with a Micro Fixture Handle and Dexterous Handling Target. Since the RPCM ORU exchange is a Space Station task, all interfaces must adhere to specifications found in the Robotics Systems Integration Standard (RSIS) (ref. 4). This RSIS states that the Dexterous Handling Target must be incorporated into all ORUs with a Micro Fixture Handle. The version of the Dexterous Handling Target used in the camera study is the result of design refinement based on tests conducted at Johnson Space Center (ref. 5). These tests have shown that the Dexterous Handling Target, when used in combination with an electronic graphic overlay (fig. 5), provides accurate information about the position and orientation of the target relative to the camera and end-effector.

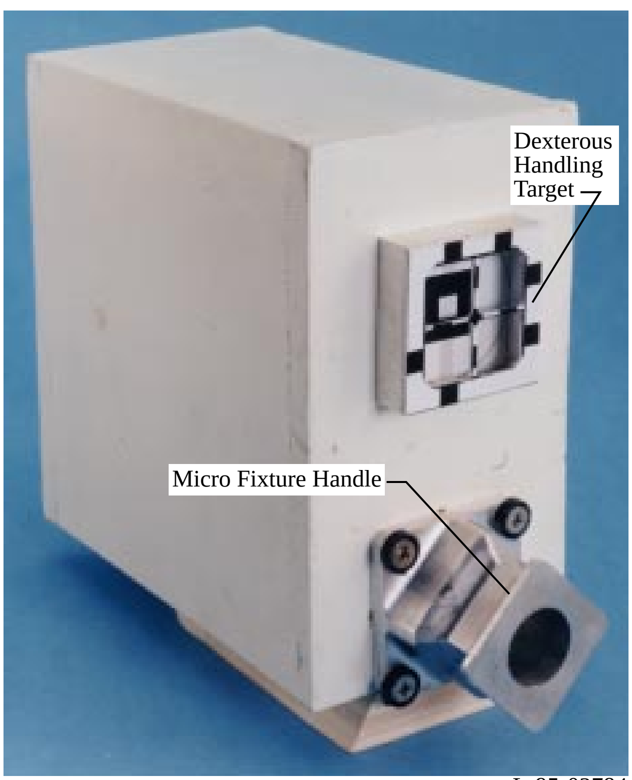

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Figure 4. Orbital Replaceable Unit.

Problem Definition

The External Maintenance Task Team report states that "camera positions and orientation coverage are critical to robotics task performance." (See ref. 6.) However, there is a difference between the wrist camera position in the FTS specifications and that recommended for use with the Dexterous Handling Target. In FTS, the camera is pitched downward, so that the operator can view the gripper fingers and use the position of the end-effector relative to the handle to determine orientation. The Dexterous Handling Target is designed based on the SPDM wrist camera configuration. At the grasp position, the wrist camera is bore sighted with the target, but the operator is no longer able to see the fingers (grippers). However, if the camera is placed in the FTS position, pitch and yaw information cannot be obtained from the Dexterous Handling Target.

The purpose of this study is to answer the following questions:

1. Is teleoperation better with the FTS wrist camera design or the SPDM design?

   There is one theory in the robotics field that it is better to pitch the wrist camera downward so that the operator can see the end-effector while performing a task. Another point of view is that the operator can rely on targets to perform tasks. If we are forced to choose between these two designs, which one is better? "Better" is defined as a more accurate positioning of the gripper with respect to the Micro Fixture Handle and a higher number of successful grasps.

2. Is it possible to combine the FTS and SPDM designs?

   Is it possible to use the Dexterous Handling Target and also see the end-effector at the same time? If this is done, can the task be performed with the same level of accuracy and success? If the wrist camera designs are combined, will error increase or decrease?

3. Does lighting have an effect on operator performance?

   Are some designs easier to use under good lighting conditions but impossible to use in a poor lighting situation? Do shadows help or hurt?

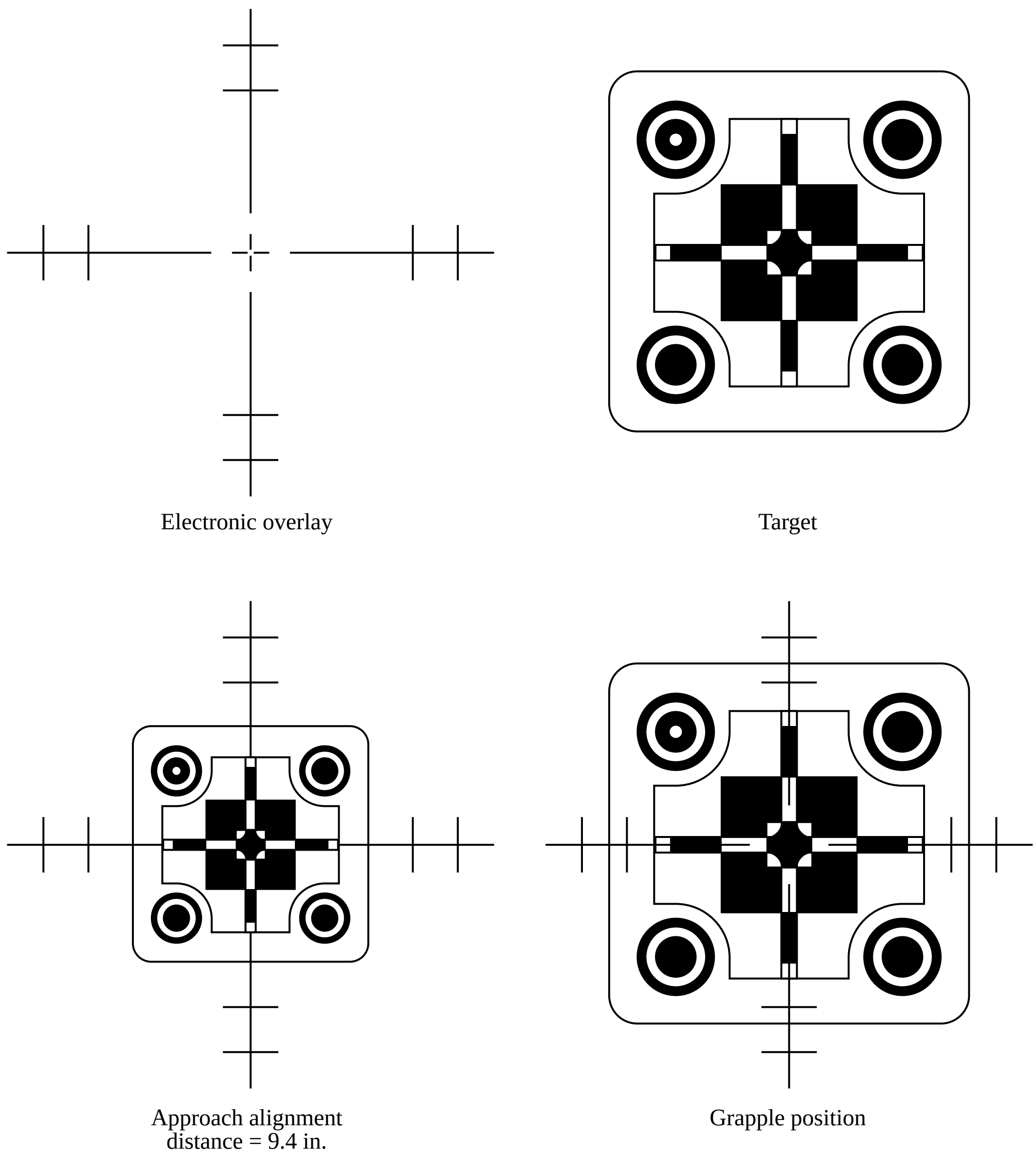

Figure 5. Using the Dexterous Handling Target. (From ref. 4.)

Experiment

HMTB Laboratory Setup

The laboratory setup for HMTB was based on specifications for the first scheduled flight of FTS known as Development Test Flight (DTF-1). The DTF-1 system was composed of two parts: a Payload Bay Element and an Aft Flight Deck Element.

The Payload Bay Element contained the seven-degree-of-freedom (shoulder roll, pitch, and yaw; elbow pitch; and wrist roll, pitch, and yaw) hydraulic manipulator (fig. 6) with a parallel jaw gripper at the end of the manipulator arm. Two wrist cameras were on the manipulator arm (fig. 7). One wrist camera, which was in accordance with FTS specifications, was pitched downward 17° so that the gripper was in the camera field of view. The second wrist camera was positioned such that at the grasp position, it was bore sighted to the Dexterous Handling Target as specified in the RSIS.

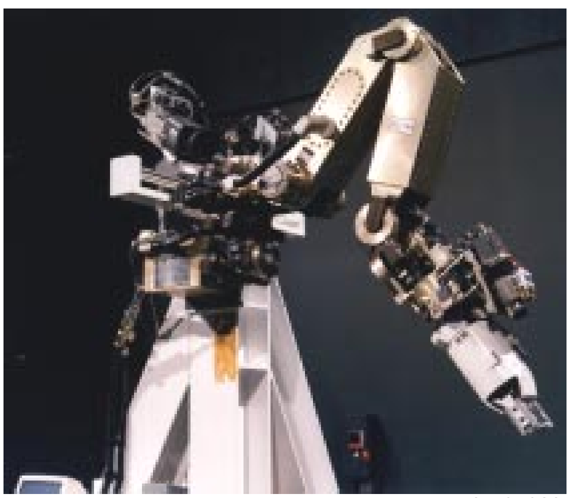
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Figure 6. Hydraulic manipulator.

The Payload Bay area also contained two shoulder (head) cameras (fig. 8) with pan, tilt, and zoom capability. The manipulator arm completely blocked the right shoulder camera view of the task work space; therefore, this camera was not used in this study. To reduce the number of variables in the experiment, the left shoulder camera was placed in a fixed position and subjects were not allowed to move the camera. Because the left shoulder camera only displayed the task work space, an additional camera was arbitrarily placed in the payload area to provide a global view of the manipulator. A global camera view may or may not be available on Space Station; therefore, its use was restricted to training.

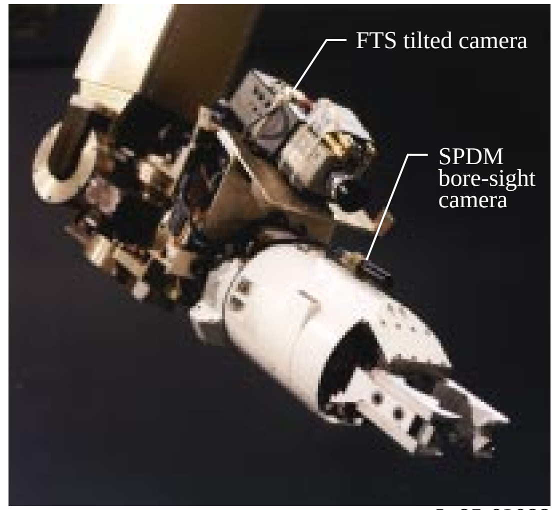

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Figure 7. Wrist cameras and manipulator grippers.

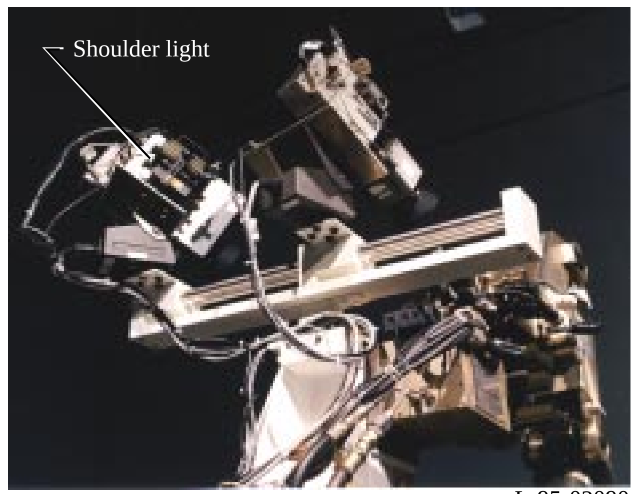

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Figure 8. Shoulder cameras and shoulder light.

The major components of the Aft Flight Deck (fig. 9) were the hand controllers, command and display panel, and video monitors. In Cartesian mode, both hand controllers (fig. 10) were used to move the manipulator with respect to a point in space: one hand controller for translation (X,Y,Z) and the other for rotation (roll, pitch, and yaw). Operators could manually input commands into the computer terminal located in the flight deck. The computer terminal displayed real-time information such as position, coordinate system, joint angles, operation mode. This display was disconnected throughout the experiment to prevent participants from obtaining position and orientation data. The manipulator in the payload bay work space could be seen either through the windows or the two video monitors. For the study, the windows were covered with a black cloth to force participants to use the video monitors. During both the

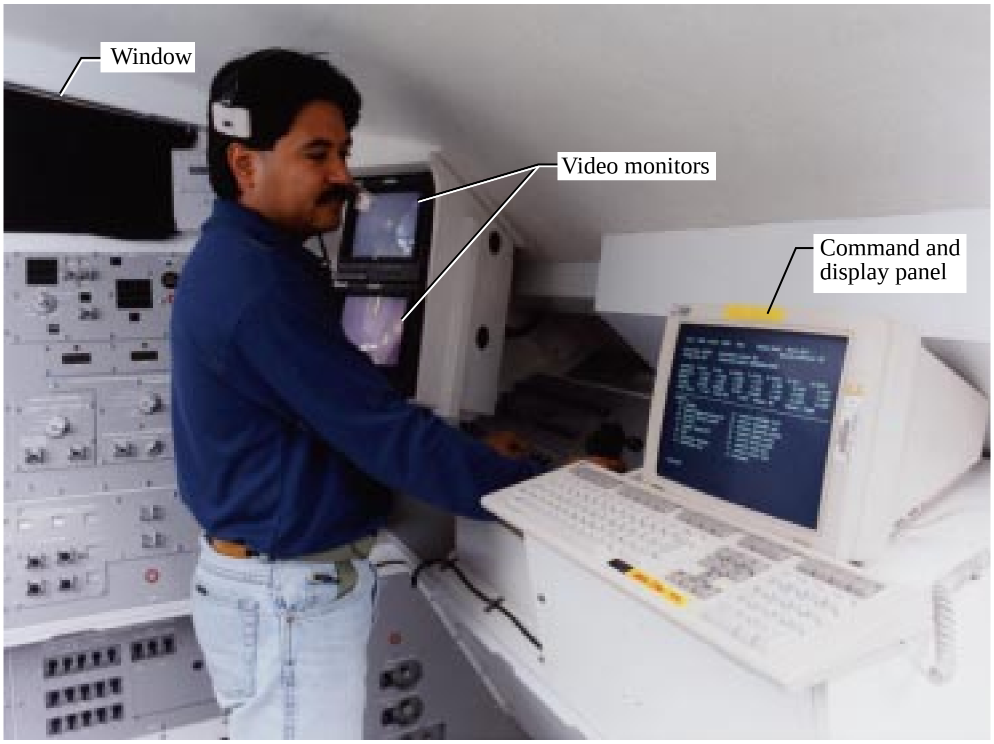

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Figure 9. Subject in Aft Flight Deck.

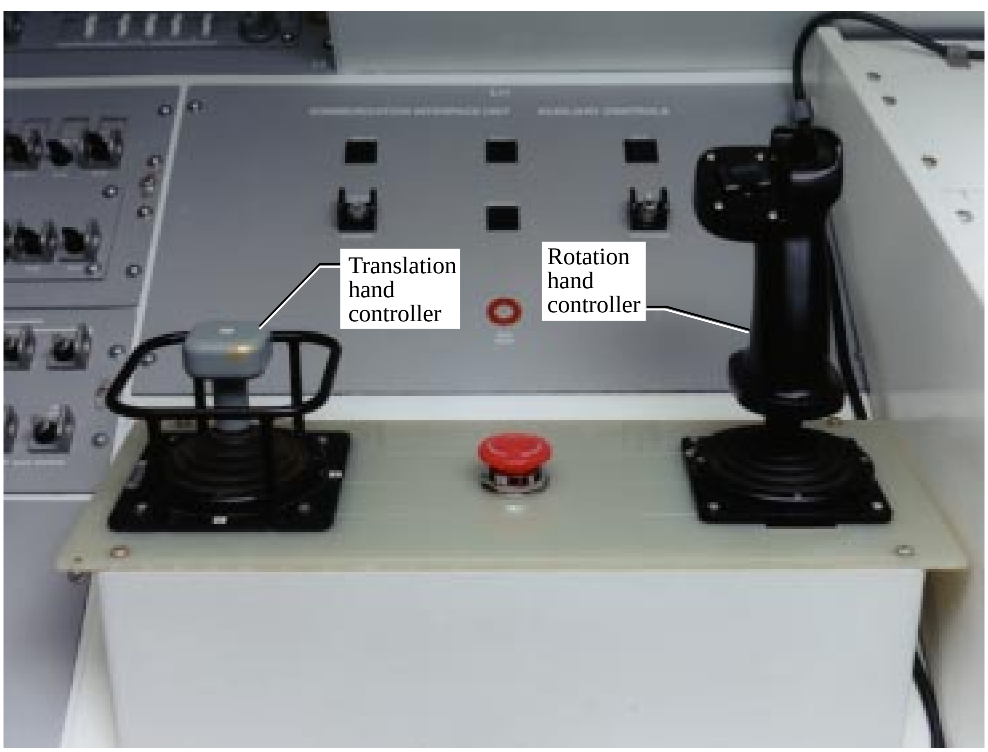

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Figure 10. Hand controllers.

training and the data collection phases of the experiment, one of the wrist camera views was transmitted to the top video monitor. The bottom monitor displayed either a global camera view (training) or left shoulder camera view (experiment).

Goal

The goal of this experiment was to compare wrist camera–target configurations for providing visual feedback during an ORU changeout task.

Subjects

Eight subjects, seven men and one woman, volunteered to participate in the study. All eight participants had some previous experience operating a robotic manipulator. One of the eight subjects had actually operated the system in the HMTB by using hand controllers in the payload bay area prior to the training. However, this subject was still considered naive because the experiment was being conducted from the flight deck not the payload bay area.

Task Procedure

Timing of the task began when subjects were given a signal to move the end-effector from the start position (fig. 11) toward the ORU. When the end-effector had been moved to the grasp position, subjects were not allowed to actually close the gripper onto the handle. This constraint was to prevent users from placing the gripper only within the vicinity of the handle and relying on force accommodation to compensate for any error. Instead, the task officially ended when the subject verbally indicated that the end-effector had been placed at the grasp position (fig. 12). The total time to complete the task and other data (e.g., joint angles, position in space) were recorded. Afterwards, the grippers were closed to determine if the subject actually reached the grasp position. The run was defined as successful only if the ORU handle was secure within the closed grippers.

Training

All participants had to become comfortable with using the hand controllers and performing the task. The global camera view allowed participants to actually see the effect of moving the hand controllers on the manipulator. To achieve the second goal, each subject performed the task with two different wrist camera–target training configurations. Training under both conditions was completed when the subject could successfully perform the task within 5 minutes twice in a row. None of the wrist camera views–target configurations in the training phase were used in the data collection portion of the experiment.

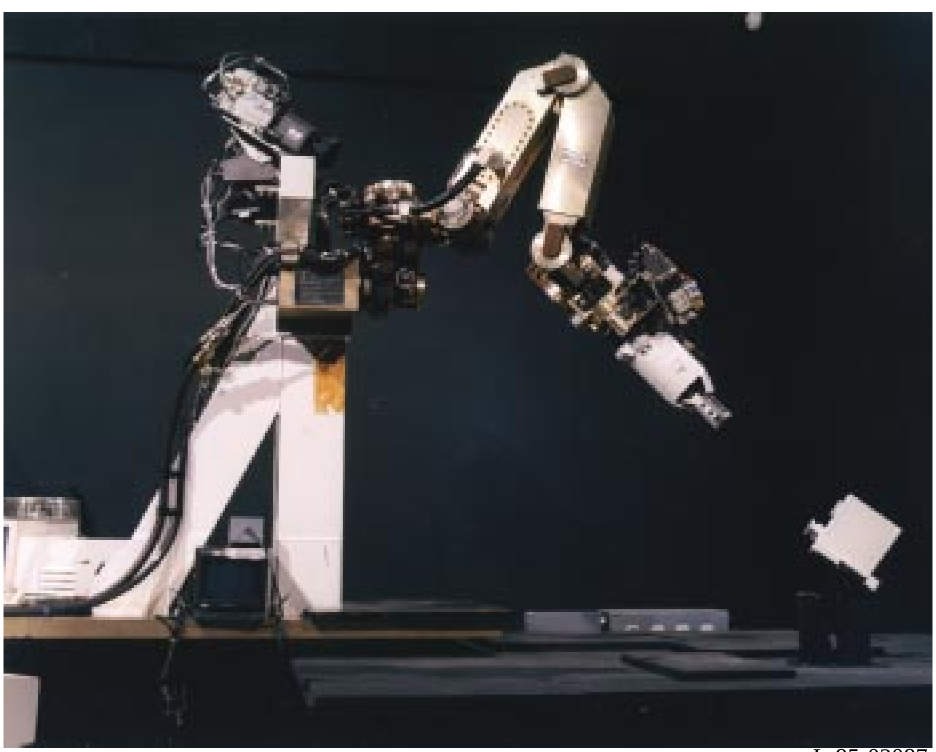

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Figure 11. Manipulator at start position.

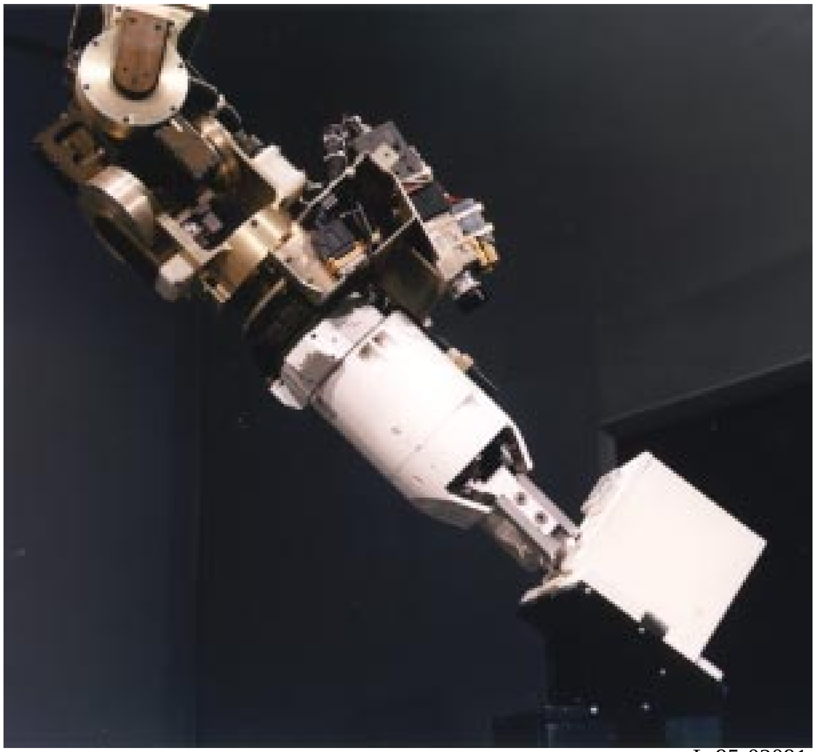

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Figure 12. Manipulator at grasp position.

Training Configuration 1

Training configuration 1 is the SPDM wrist camera, bore sighted, with 15-mm lens, target, and electronic graphic overlay. (See fig. 13.) With a 15-mm lens, the target fills the entire wrist camera field of view when the end-effector is near the grasp position. This view forces the subject to use the graphic overlay and Dexterous Manipulation Target to align the gripper with the handle on the ORU.

Training Configuration 2

Training configuration 2 is the FTS wrist camera, pitched downward 17° with 12.5-mm lens, target, and no overlay. In this configuration, the subject can see the grippers of the manipulator at the grasp position. Although the Dexterous Manipulation Target is still within the camera field of view, it cannot be used properly because a graphic overlay has not been provided and the camera is pitched downward 17°. As a result, the subject must rely primarily on the position of the gripper relative to the ORU and target to determine the grasp position.

Experiment Design

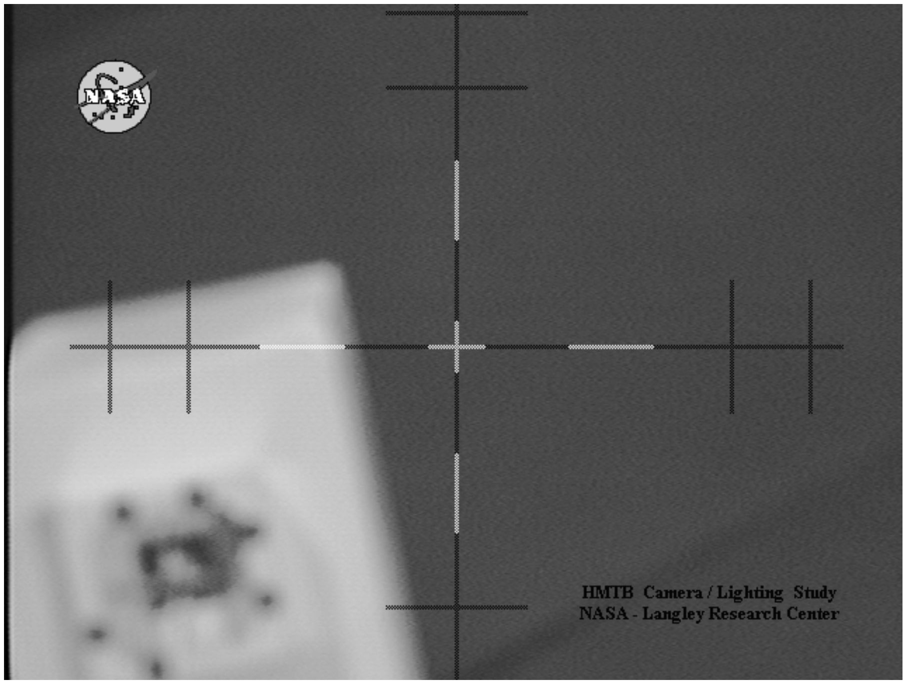
To answer the three questions in the section “Problem Definition,” four wrist camera setups were examined under two lighting conditions to produce eight different experiment configurations. Each subject performed the task by using a unique sequence of the eight wrist camera, target, and lighting configurations based on the Latin square design (ref. 7) in figure 14. The Latin square was used to eliminate the effect of improvements in performance due to learning. A total of 64 runs, 8 runs (1 data set) for each of the 8 configurations, was completed by each subject.

Wrist Camera–Target Configurations

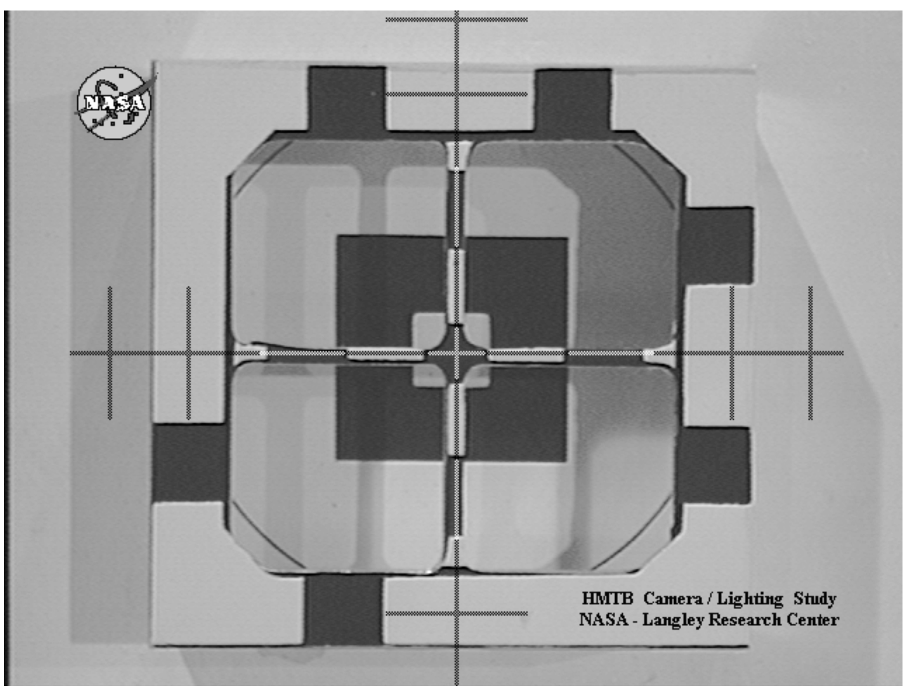
Experiment Configuration A (SPDM Design)

Experiment configuration A (fig. 15[1]) is a bore-sighted camera with 7.5-mm lens, electronic graphic overlay, and overhead lights. Setup was based on specifications for SPDM. Subjects were unable to see grippers at grasp position and had to rely on target and overlay for alignment. All overhead lights (normal laboratory lighting fixtures) were turned on.

[1]Figures 15–24 are at the end of the section “Wrist Camera–Target Configurations.”



(a) Start position.



(b) Grasp position.

Figure 13. Training configuration 1.

Data set \ Subject	1	2	3	4	5	6	7	8
1	A	B	C	D	E	F	G	H
2	B	E	A	F	C	H	D	G
3	C	A	D	B	G	E	H	F
4	D	F	B	H	A	G	C	E
5	E	C	G	A	H	B	F	D
6	F	H	E	G	B	D	A	C
7	G	D	H	C	F	A	E	B
8	H	G	F	E	D	C	B	A

Figure 14. Latin square design.

Experiment Configuration B (FTS Design)

Experiment configuration B (fig. 16) is a pitched camera with 12.5-mm lens, no overlay, overhead lights, and no target; camera was pitched downward 17°. Camera focal length was still within the range in DTF-1 specifications. A target and overlay were not provided; therefore, subjects had to rely on gripper with respect to ORU and handle for alignment.

Experiment Configuration C (Modified FTS Design)

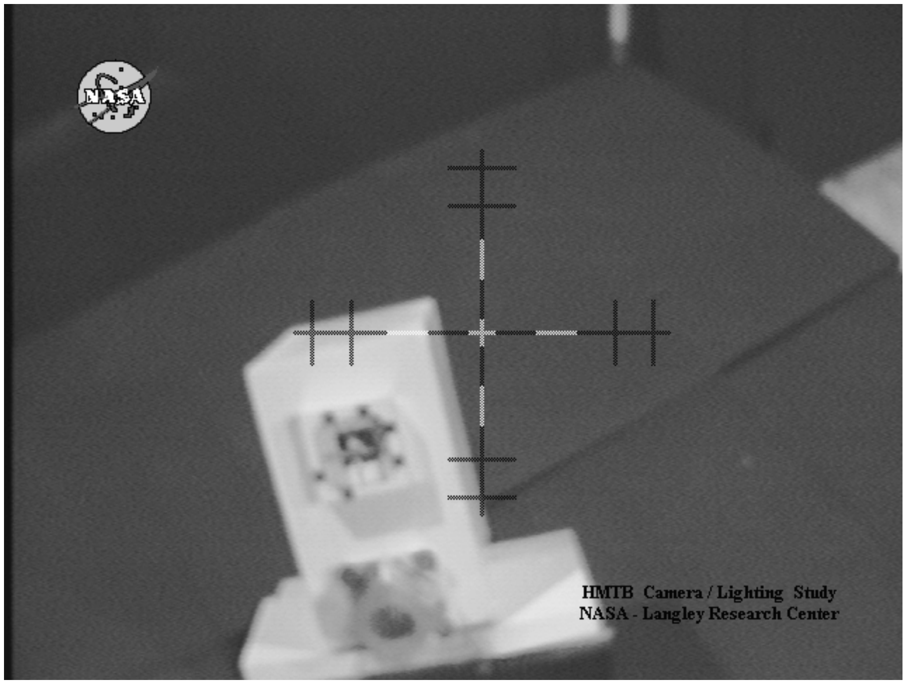
Experiment configuration C (fig. 17) is a pitched camera with 12.5-mm lens, electronic graphic overlay, overhead lights, and target. Configuration C is the same as configuration B except a target and graphic overlay were provided. Pitch and other orientation information were difficult to obtain from the target because it was designed for a bore-sighted, not pitched, camera. Subjects could see the grippers at the grasp position.

Experiment Configuration D (Modified SPDM Design)

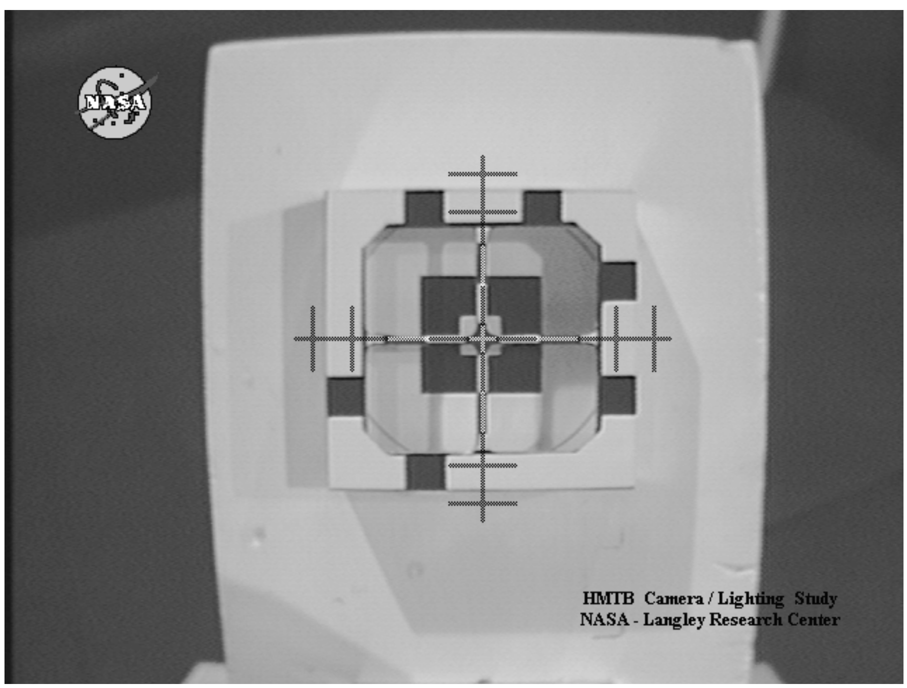
Experiment configuration D (fig. 18) is a bore-sighted camera with 4-mm lens, electronic graphic overlay, and overhead lights. Wrist camera was bore sighted to the target at the grasp position. Configuration D is similar to configuration A except the focal length was smaller. This shorter focal length expands the field of view so that the target and grippers could be seen.

Experiment Configurations E, F, G, and H

Experiment configurations E, F, G, and H (figs. 19 to 22) are the same as configurations A, B, C, and D, respectively, except the amount of lighting was reduced. All overhead lights were turned off and the left shoulder and wrist camera lights were turned on (fig. 23). The left shoulder light (fig. 8) complied with all DTF-1 shoulder light specifications except luminance coverage. The wrist camera lighting unit (fig. 24) installed was actually designed for the Automated Structural Assembly Laboratory (ASAL). (See ref. 8.) This unit provided lighting for close-up positions when the manipulator either blocked shoulder lights or produced shadows. It was not based on DTF-1 specifications but was intended to test the effects of wrist lighting.

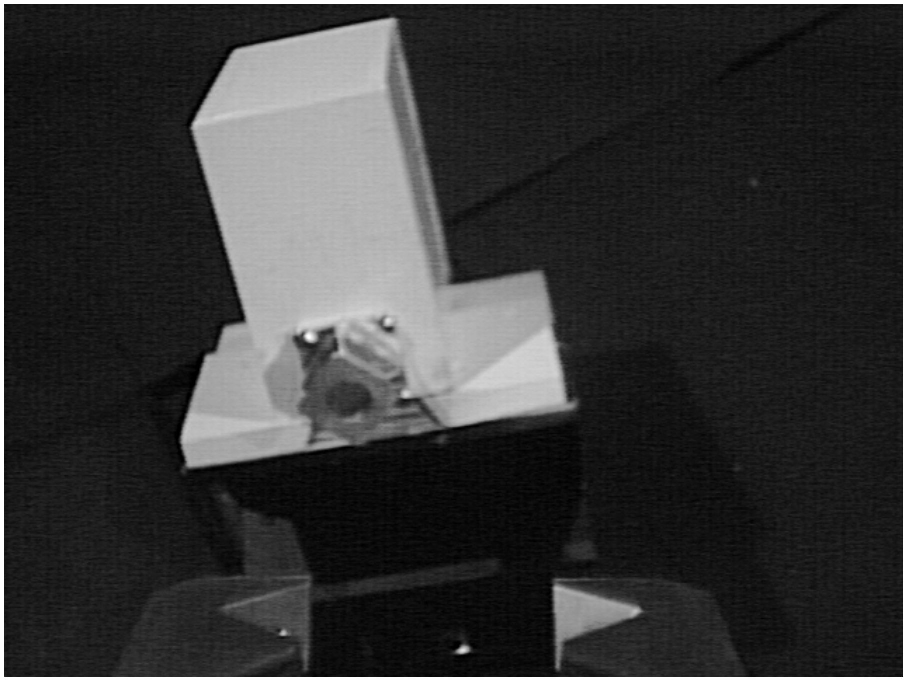


(a) Start position.

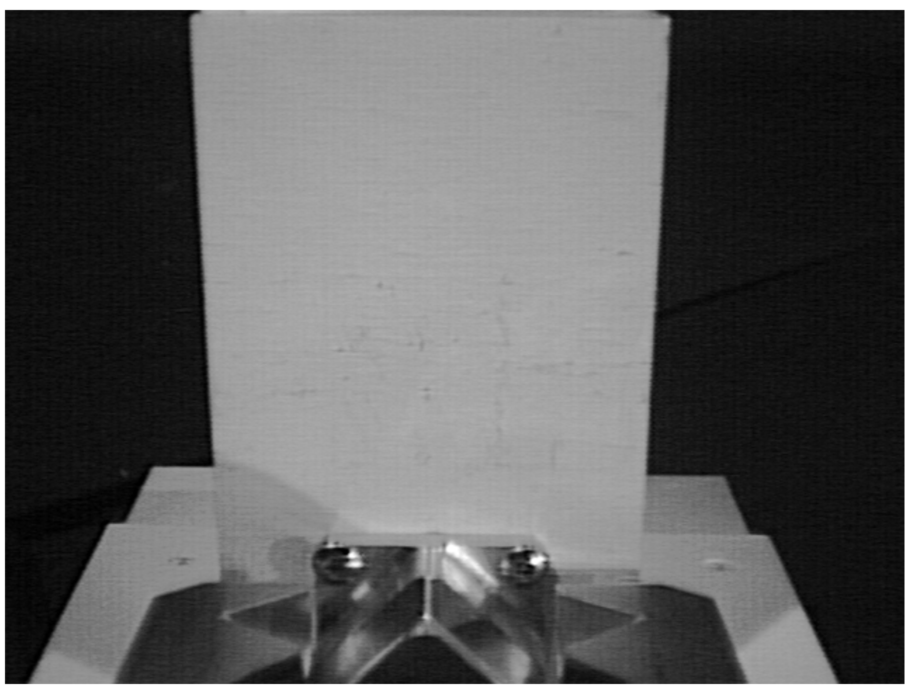


(b) Grasp position.

Figure 15. Experiment configuration A.

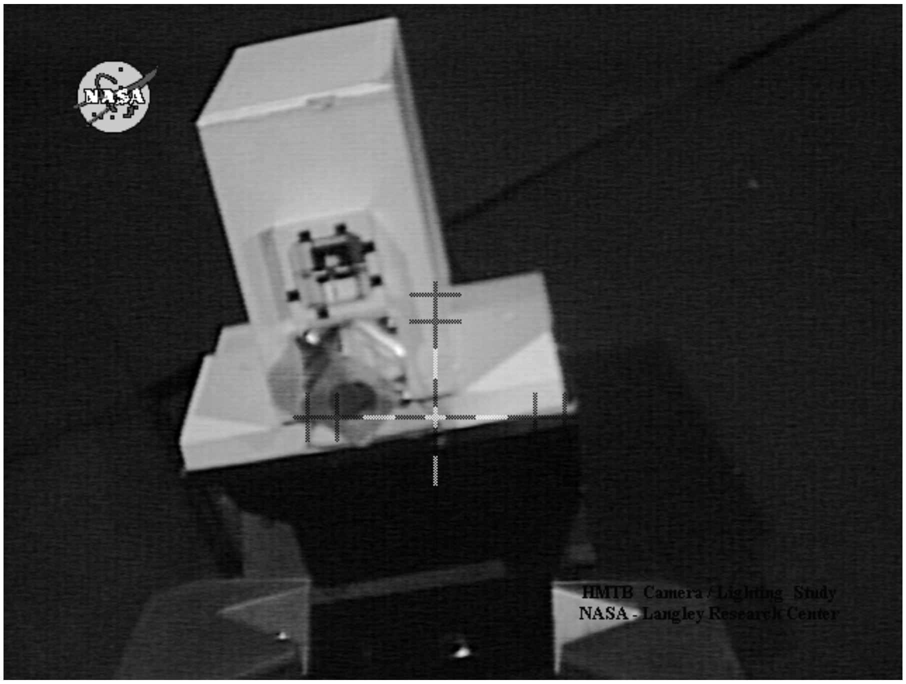


(a) Start position.

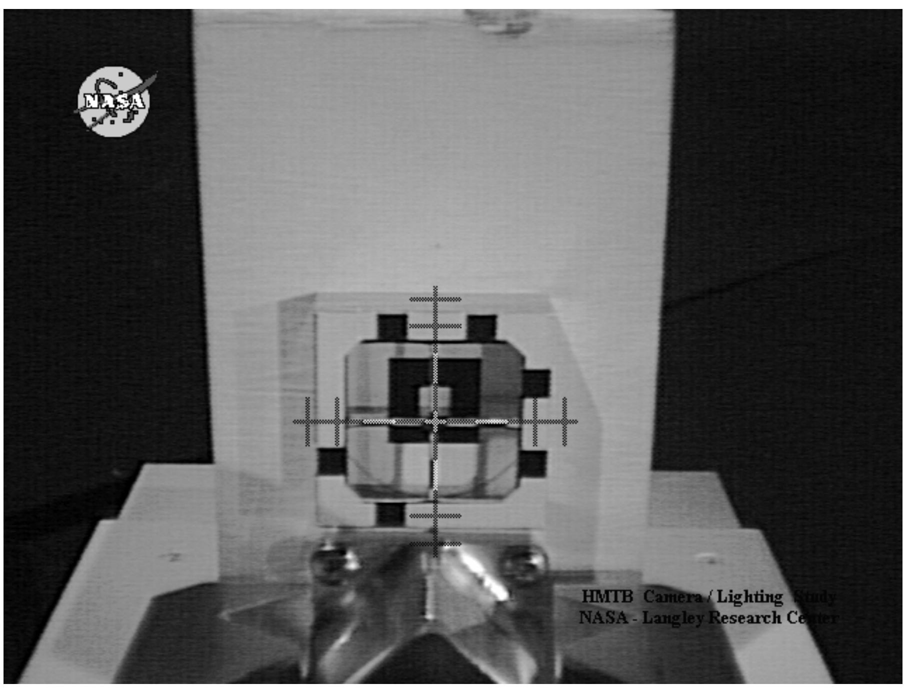


(b) Grasp position.

Figure 16. Experiment configuration B.

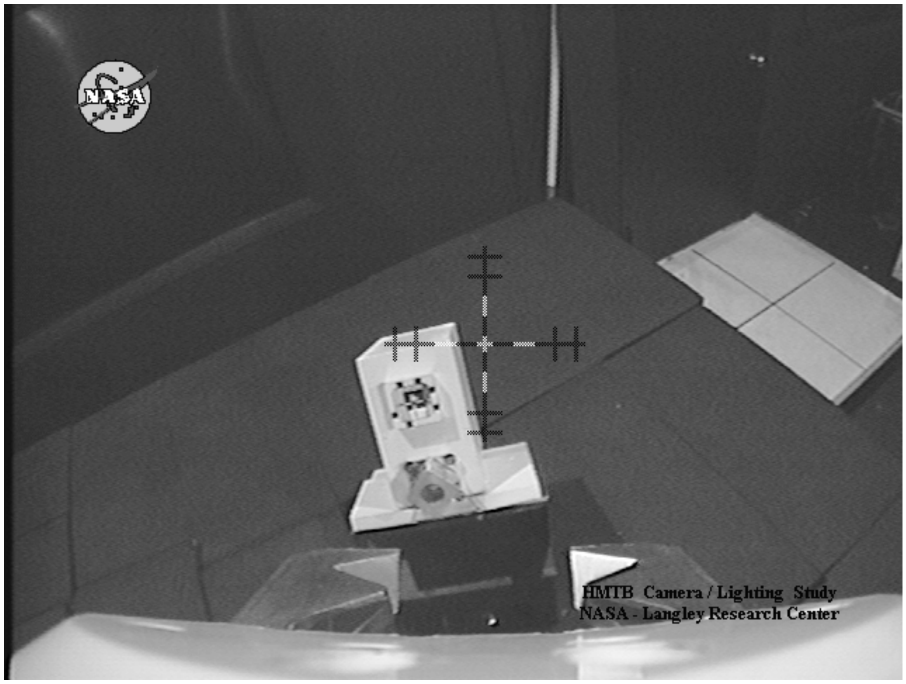


(a) Start position.

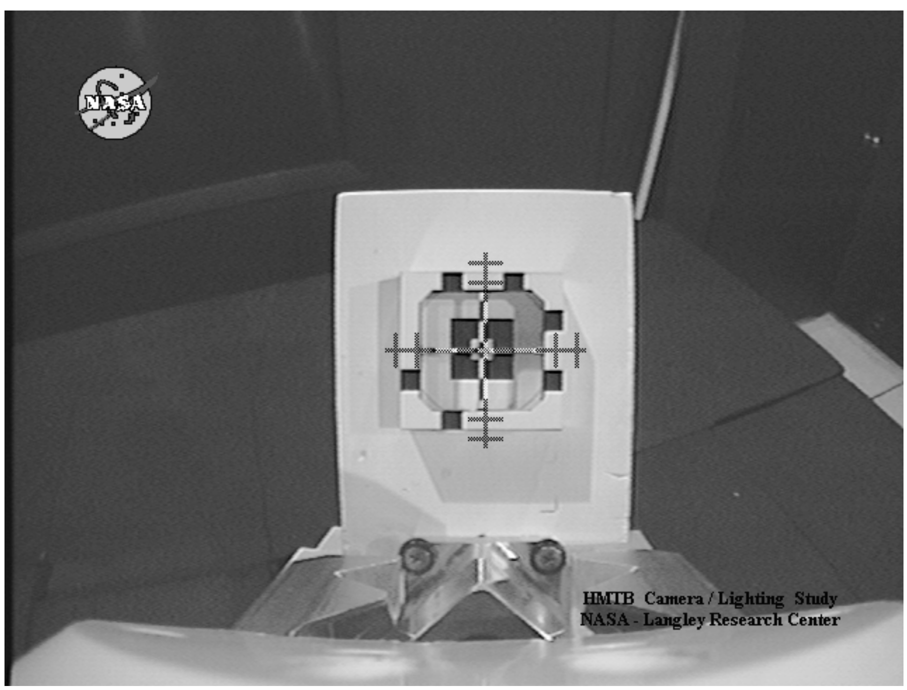


(b) Grasp position.

Figure 17. Experiment configuration C.

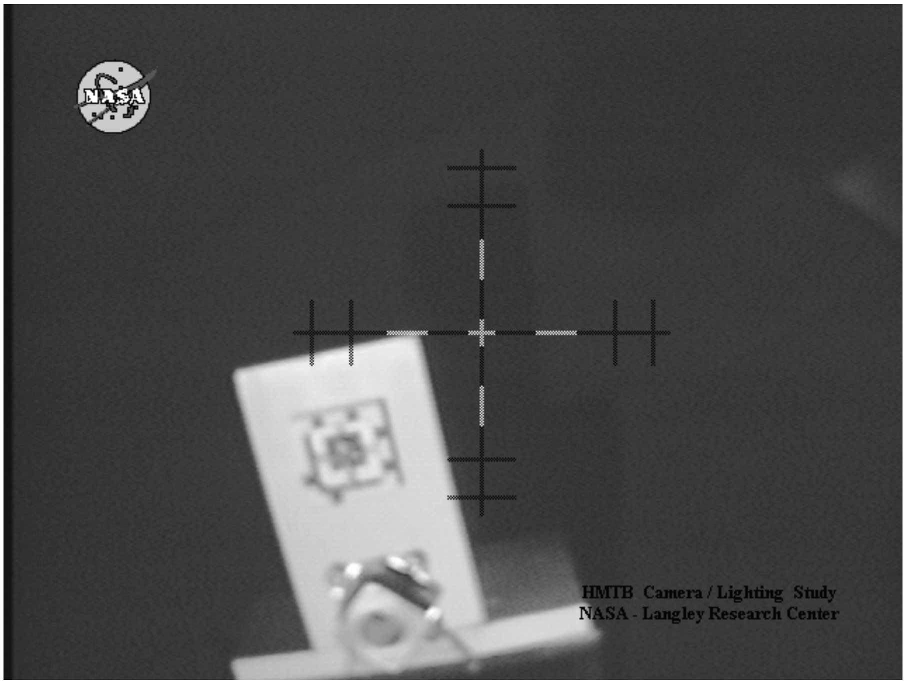


(a) Start position.

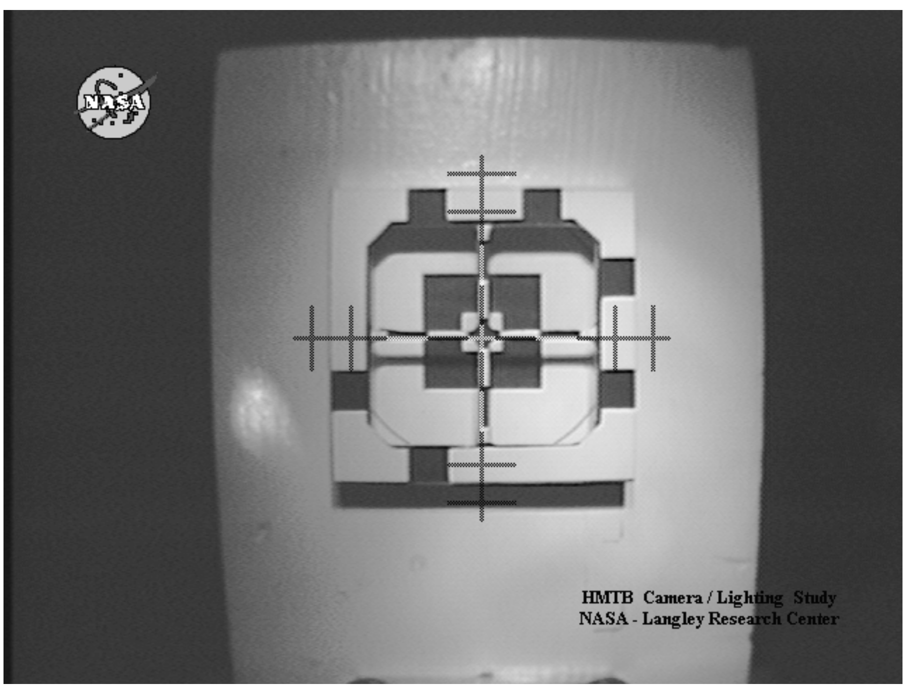


(b) Grasp position.

Figure 18. Experiment configuration D.

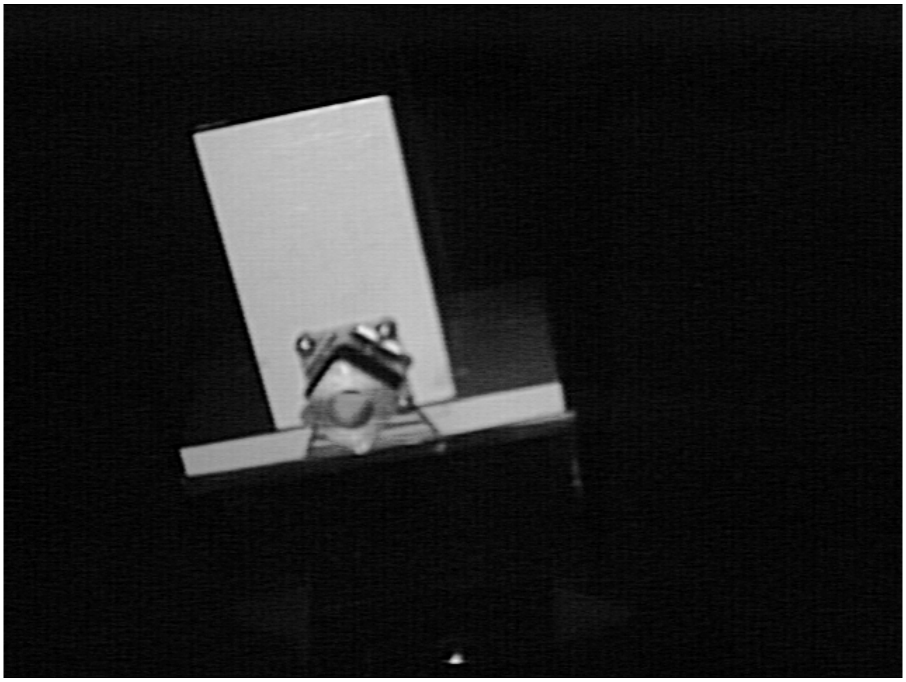


(a) Start position.

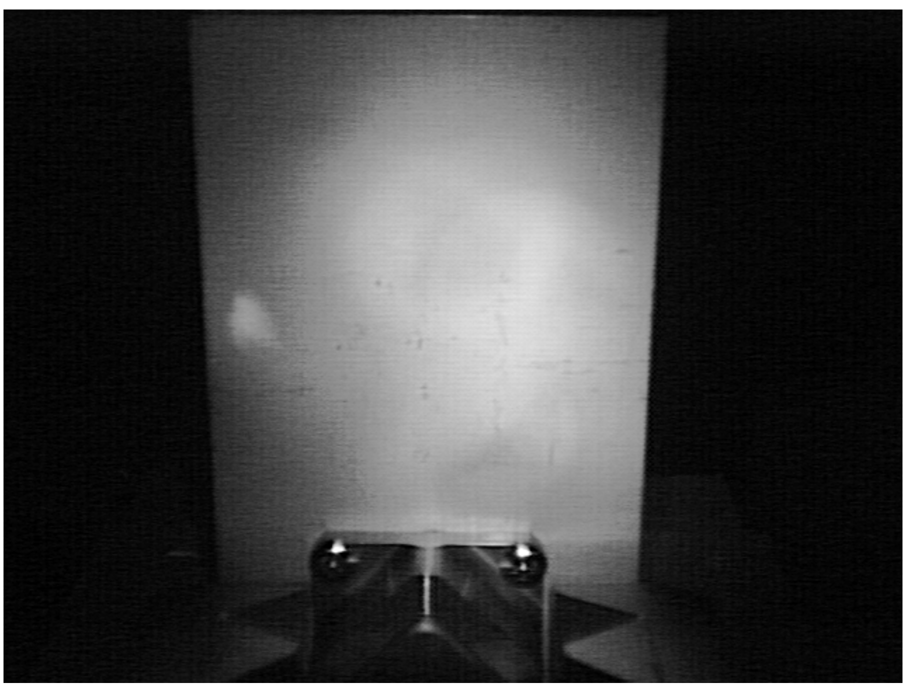


(b) Grasp position.

Figure 19. Experiment configuration E.

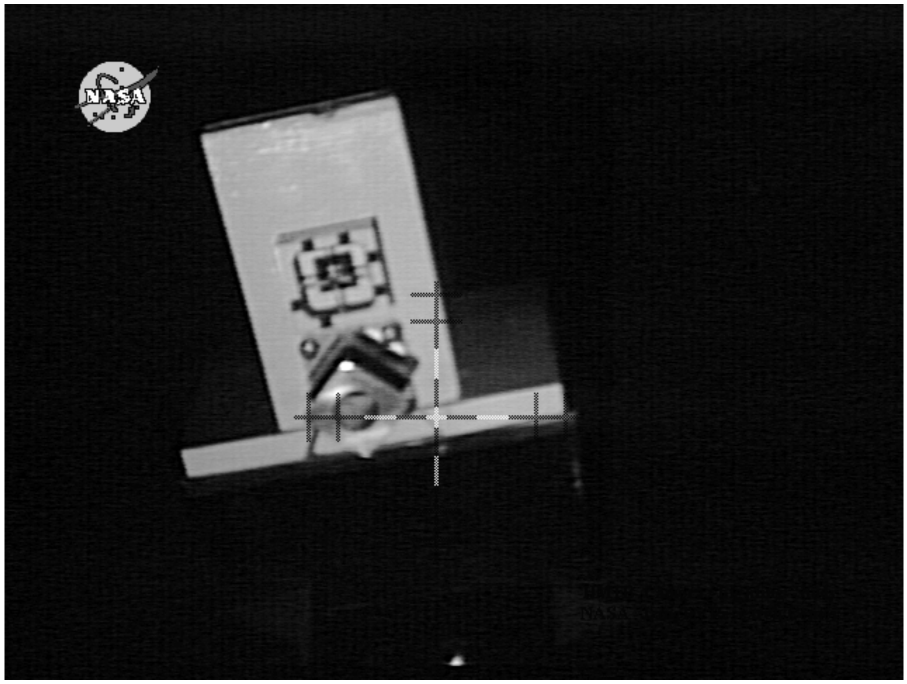


(a) Start position.

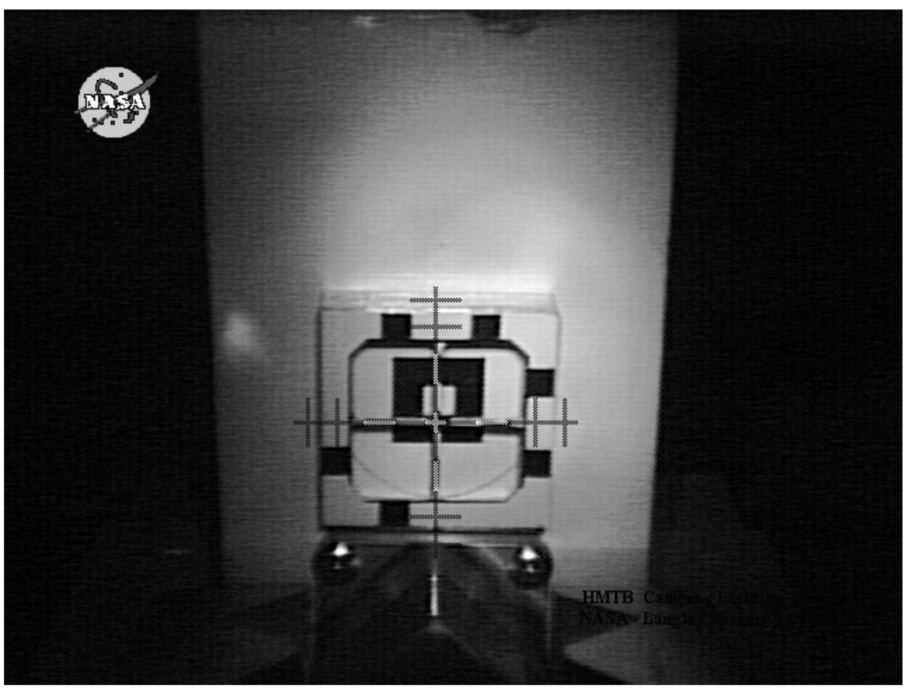


(b) Grasp position.

Figure 20. Experiment configuration F.

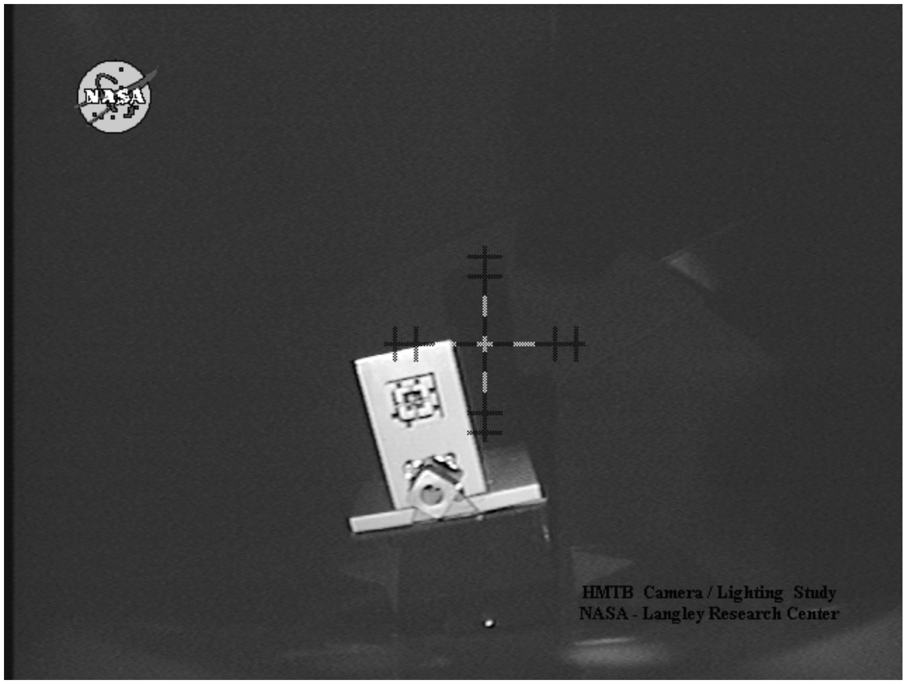


(a) Start position.

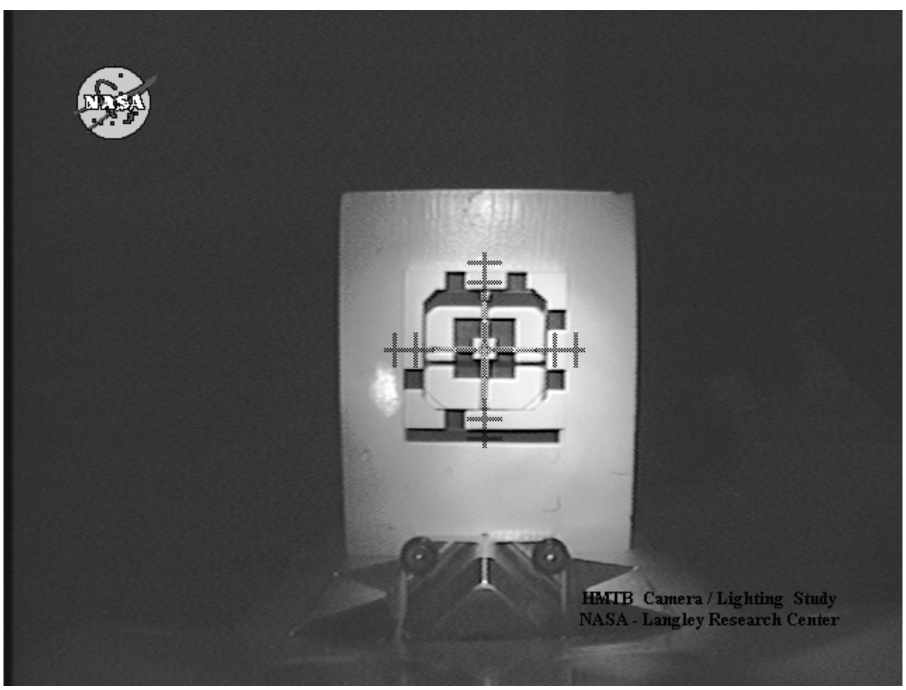


(b) Grasp position.

Figure 21. Experiment configuration G.



(a) Start position.



(b) Grasp position.

Figure 22. Experiment configuration H.

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Figure 23. HMTB under minimum lighting conditions.

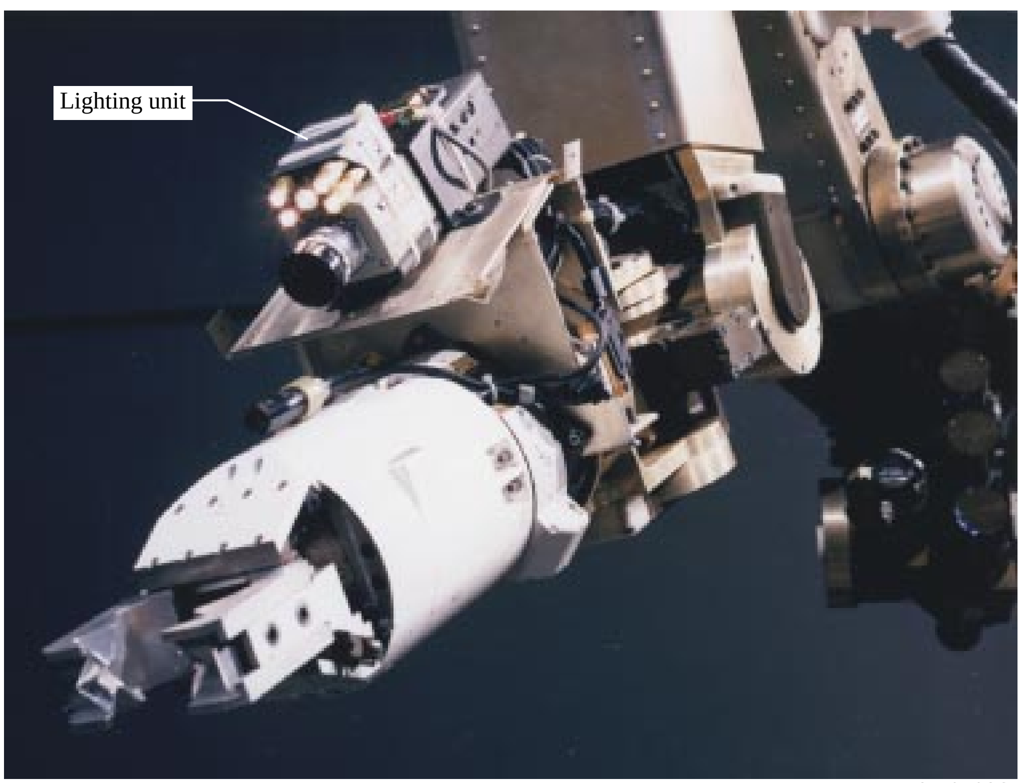

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Figure 24. Wrist camera lighting unit.

Results

Eight Latin squares were created by using the following variables for each square: number of successful gripper closures; total task completion time; *X*-, *Y*-, and *Z*-axis translation error; and roll, pitch, and yaw error. Analysis of Variance (ANOVA) tables (tables 1 to 8) were created for every Latin square (ref. 9). The first column indicates whether the source of variation is due to rows (data sets), columns (subjects), treatments (wrist camera–target configurations), or error. The remaining ANOVA table columns in order are the sum of squares (SS), degrees of freedom (df), mean square (MS), *F*-ratio (*F*), and probability value (Prob > *F*).

Table 1. ANOVA Table for Successful Gripper Closures

[Boldface type indicates probability value less than 0.01]

Source	Successful gripper closures				
	SS	df	MS	*F*	Prob > *F*
Data sets	20.4375	7	2.919643	1.36	0.2455
Subjects	33.6875	7	4.8125	2.25	0.0489
Configurations	66.9375	7	9.5625	4.47	**0.0009**
Error	89.875	42	2.139881		
Total	210.9375	63			

Table 2. ANOVA Table for Completion Time

[Boldface type indicates probability value less than 0.01]

Source	Completion time, min				
	SS	df	MS	*F*	Prob > *F*
Data sets	5.412107	7	0.7731581	5.13	**0.0003**
Subjects	7.260264	7	1.037181	6.88	**0.0000**
Configurations	0.9648506	7	0.1378358	0.91	0.5050
Error	6.33103	42	0.1507388		
Total	19.96825	63			

Table 3. ANOVA Table for *X*-Axis Translation Error

Source	*X*-axis translation error, in.				
	SS	df	MS	*F*	Prob > *F*
Data sets	0.4628669	7	.06612	1.17	0.3388
Subjects	0.4298225	7	.06140	1.09	0.3876
Configurations	0.2879608	7	.04113	0.73	0.6479
Error	2.368396	42	.05639		
Total	3.549046	63			

Table 4. ANOVA Table for *Y*-Axis Translation Error

Source	*Y*-axis translation error, in.				
	SS	df	MS	*F*	Prob > *F*
Data sets	0.829433	7	0.1184904	1.07	0.4022
Subjects	0.6565122	7	0.09378	0.84	0.5582
Configurations	0.9624309	7	0.1374901	1.24	0.3051
Error	4.671101	42	0.1112167		
Total	7.119477	63			

Table 5. ANOVA Table for *Z*-Axis Translation Error

Source	*Z*-axis translation error, in.				
	SS	df	MS	*F*	Prob > *F*
Data sets	0.1705924	7	0.02437	1.21	0.3189
Subjects	0.3777076	7	0.05395	2.68	0.0219
Configurations	0.1294663	7	0.01849	0.92	0.5024
Error	0.8462137	42	0.02014		
Total	1.52398	63			

Table 6. ANOVA Table for Roll Error

Source	Roll error, rad				
	SS	df	MS	*F*	Prob > *F*
Data sets	0.0006289	7	0.00008984	0.79	0.5989
Subjects	0.0006007	7	0.00008581	0.76	0.6271
Configurations	0.001948	7	0.0002783	2.45	0.0335
Error	0.004770	42	0.0001135		
Total	0.007948	63			

Table 7. ANOVA Table for Pitch Error

[Boldface type indicates probability value less than 0.01]

Source	Pitch error, rad				
	SS	df	MS	*F*	Prob > *F*
Data sets	0.0007362	7	0.0001051	0.65	0.7082
Subjects	0.007923	7	0.001131	7.05	**0.0000**
Configurations	0.0007255	7	0.0001036	0.65	0.7159
Error	0.006745	42	0.0001605		
Total	0.01613	63			

Table 8. ANOVA Table for Yaw Error

Source	Yaw error, rad				
	SS	df	MS	*F*	Prob > *F*
Data sets	0.0009836	7	0.0001405	0.68	0.6841
Subjects	0.002511	7	0.0003588	1.75	0.1238
Configurations	0.001212	7	0.0001732	0.84	0.5575
Error	0.008619	42	0.0002052		
Total	0.01332	63			

The F-ratio and probability value were used to evaluate the results of the experiment. The null hypothesis (H_0), which is that all the means are the same, was tested against the alternative hypothesis (H_1), which is that there is at least one mean that is different. Mathematically (refs. 10 and 11), this is written as

$$H_0: \ \mu_1 = \mu_2 = \ldots = \mu_k$$
$$H_1: \ \text{not all } \mu_i \text{ are the same}$$

where

i = 1, 2, …, k

k order of Latin square, 8

The observed F-ratio is MS_t/MS_{error}, where t is defined as data set, subject, or configuration. The probability value is the probability that the F-ratio obtained from an F-distribution table is greater than the observed F-ratio. The value that we look up in the F-distribution table is as follows:

$$F(\alpha; r_1, r_2)$$

where

α significance level

r_1 degrees of freedom in numerator (population)

r_2 degrees of freedom in denominator (error)

If the probability value is less than or equal to α, we accept H_1, otherwise we accept H_0. For all tests, $\alpha = 0.01$ was used. Instances in which the probability value is less than 0.01 are highlighted in boldface type in the column Prob > F in the ANOVA tables. If statistically the means are all determined to be equal, that variable is not used for comparison purposes.

Data Sets

Average completion time (fig. 25) is the only variable that is statistically significant in comparing data sets; this was expected because it indicated a learning curve. The assumption was made that subjects would be able to perform the tasks more quickly as the number of trials increased. At the end of the study, subjects were able to complete the task in almost half the time it took at the beginning of the study.

Subjects

Two of the eight variables are statistically significant in comparing subjects: average task completion time and pitch error. The differences in completion time (fig. 26) between subjects indicate the various levels of robotics experience subjects possessed prior to the study. Figure 27 is the result of several subjects experiencing trouble distinguishing between pitch error and Z-axis translation error.

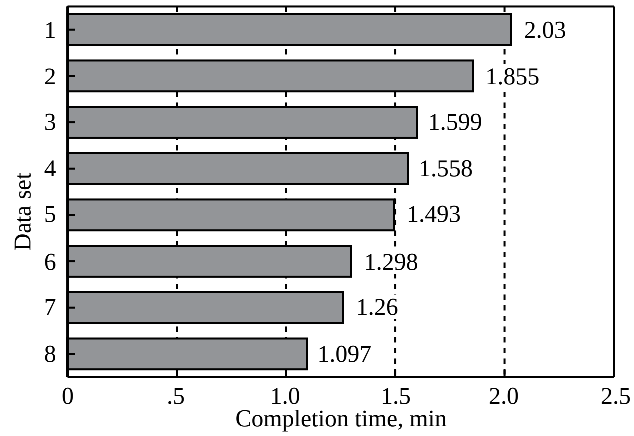

Figure 25. Average task completion time for each data set.

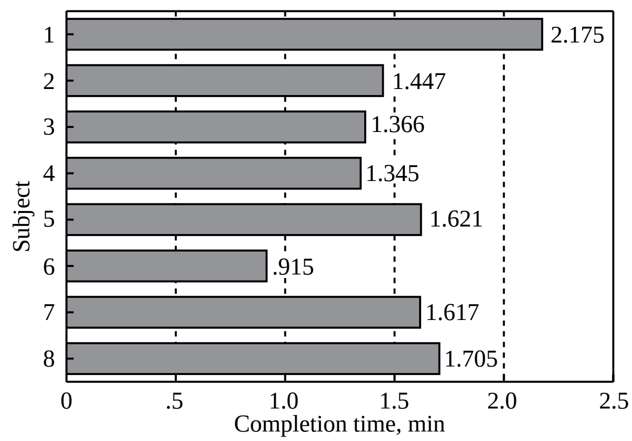

Figure 26. Average task completion time for each subject.

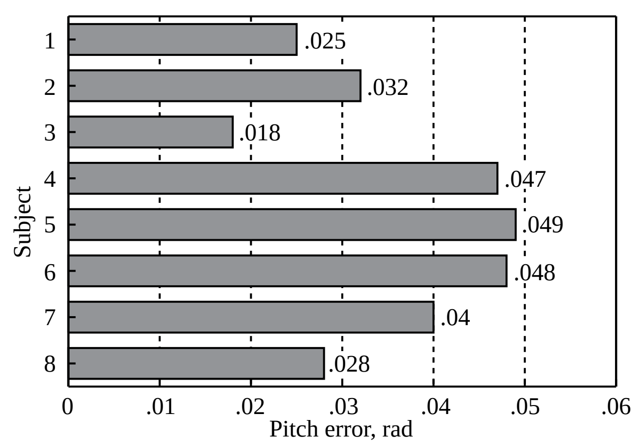

Figure 27. Average pitch error for each subject.

Configurations

The only variable with significant mean differences between configurations is number of successful gripper closures (fig. 28 and table 9). Because the goal of this study is to compare wrist camera and target configurations, this figure and table are used to answer the questions posed in the section "Problem Definition."

Table 9. Average Number of Gripper Closures for Each Configuration Normalized About Mean

Configuration	Description	Gripper closures: Average number	Gripper closures: Normalized about mean	Gripper closures: Difference from mean, percent
Maximum lighting				
A	SPDM	6.75	1.18	+18
B	FTS	6.125	1.07	+7
C	Modified FTS	5.875	1.03	+3
D	Modified SPDM	7.0	1.22	+22
Minimum lighting				
E	SPDM	5.875	1.03	+3
F	FTS	3.5	0.61	−39
G	Modified FTS	5.0	0.87	−13
H	Modified SPDM	5.625	0.98	−2
Mean		5.72		

FTS Design (Configurations B and F) Versus SPDM Design (Configurations A and E)

First, for successful gripper closures under maximum lighting conditions, the bore-sighted camera–target configuration (configuration A) is 11 percent better than the pitched camera (configuration B). However, when the task is performed under minimal lighting conditions, the bore-sighted camera (configuration E) is 42 percent better than the pitched camera (configuration F). Therefore, if we had to choose between the FTS or SPDM wrist camera design, the SPDM design is clearly better.

Combining Dexterous Handling Target With View of End-Effector

The two approaches to creating this scenario (combining target with end-effector view) are as follows:

Modified FTS (configurations C and G)—Take the FTS wrist camera setup (configurations B and F) and add the Dexterous Handling Target and graphic overlay.

Modified SPDM (configurations D and H)—Take the SPDM wrist camera setup (configurations A and E) and change the focal length from 7.5 mm to 4 mm. This change widens the field of view so that the end-effector can now be seen.

Modified FTS design (configurations C and G) versus FTS design (configurations B and F). Under good lighting conditions, the number of gripper closures for the FTS design (configuration B) is 4 percent better than the modified FTS (configuration C). However under poor lighting conditions, for the modified FTS (configuration G), the number of gripper closures is 26 percent higher than those for the original FTS design (configuration F). As a result, we can conclude that adding the Dexterous Handling Target and graphic overlay to the FTS wrist camera design improves performance.

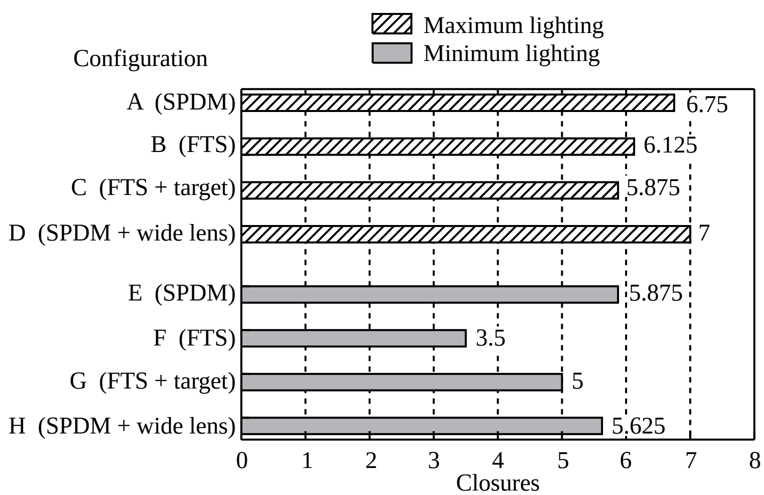

Figure 28. Average number of successful gripper closures for each configuration.

Modified SPDM design (configurations D and H) versus SPDM design (configurations A and E). Under good lighting conditions, the number of successful gripper closures in the modified SPDM design (configuration D) is 4 percent better than the number for the SPDM design (configuration A). However under poor lighting, the number of gripper closures for the modified SPDM design (configuration H) is 5 percent worse than for the SPDM design (configuration E). Therefore, changing the field of view on the SPDM design decreases performance.

Modified SPDM design (configurations D and H) versus FTS design (configurations B and F). The number of successful closures is 15 percent (maximum lighting) and 37 percent (minimum lighting) better with the modified SPDM design than the FTS design. Therefore, the SPDM design with a wider field of view is still better than the FTS pitched wrist camera concept.

Effects of Lighting Changes

The number of successful gripper closures for each configuration decreases under poor lighting conditions. However, the number of gripper closures for the FTS design under poor lighting (configuration F) is approximately half the number under maximum lighting (configuration B). This result suggests that good lighting is a necessity in order to perform the task by using the FTS design.

Concluding Remarks

The SPDM (Special Purpose Dexterous Manipulator) wrist camera design (bore-sighted wrist camera with Dexterous Handling Target and electronic graphic overlay) is better than the FTS (Flight Telerobotic Service) design (pitched wrist camera with a view of the end-effector). If the Dexterous Handling Target and overlay are added to the FTS design, accuracy increases. If the field of view for the SPDM design is changed so that the end-effector can be seen, accuracy decreases. However, the SPDM design with the wider field of view is still better than the original FTS design. Reducing the amount of light in the work space makes performing the ORU changeout task much more difficult with the FTS design but only slightly more difficult for all other configurations.

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13. ABSTRACT *(Maximum 200 words)*

The Hydraulic Manipulator Testbed (HMTB) is the kinematic replica of the Flight Telerobotic Servicer (FTS). One use of the HMTB is to evaluate advanced control techniques for accomplishing robotic maintenance tasks on board the Space Station. Most maintenance tasks involve the direct manipulation of the robot by a human operator when high-quality visual feedback is important for precise control. An experiment was conducted in the Systems Integration Branch at the Langley Research Center to compare several configurations of the manipulator wrist camera for providing visual feedback during an Orbital Replaceable Unit changeout task. Several variables were considered such as wrist camera angle, camera focal length, target location, lighting. Each study participant performed the maintenance task by using eight combinations of the variables based on a Latin square design. The results of this experiment and conclusions based on data collected are presented.

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